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Materials Science and Engineering A 395 (2005) 116–123

MATERIALS SCIENCE & ENGINEERING A

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Feasibility of producing optimal surface integrity by process design in hard turning

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Received 16 August 2004; received in revised form 2 December 2004; accepted 6 December 2004

Abstract

There is a growing demand in hard turning industry to produce favorable surface integrity (surface finish, microstructure, microhardness, and residual stress) for improving component performance. Suitable process parameters will produce certain favorable surface integrity or at least avoid detrimental phase transformations to component performance. It is not clear if surface integrity is controllable using a set of selected process parameters. This research is to study the feasibility of obtaining four distinct types of surface integrity, which may have potential dramatic effects on fatigue life of hard-machined components. This study identifies surface integrity first and follows with the necessary conditions possible to create it in hard turning. Favorable surface integrity for optimal fatigue life can be produced using small feeds and sharp cutting tools. From the process point of view, tool wear is the dominant factor to promote white layer formation and yields a large variance of surface roughness, which may significantly deteriorate component life. A white layer could be more than 30% harder and a dark layer about 60% softer than the bulk material.

Keywords: Surface integrity; White layer; Hard turning; Tool wear

1. Introduction

Precision-machined components typically fall into two categories, hard turned or ground. Since the late 1970s hard turning, the turning of material with hardness greater than 45 HRC, has become economically, environmentally, and technically competitive when compared to grinding [1]. Surface integrity is a qualitative as well as quantitative description of both the surface and subsurface of a component. Some of the properties commonly considered in surface integrity include, but not limited to, surface topography, surface and subsurface hardness, microstructure, residual stresses, etc. Hard turning has the advantage of a single cutting edge, capable of 'controlling' the surface integrity of the machined part through different machining parameters. With this capability, manufacturers may be able to design a machining process for optimal surface integrity to maximize component life in service. But to be able to "design" a process, one must understand the effects of process parameters on component surface integrity. Hard turning may induce a deep compressive residual stress in the subsurface, while it may also produce a phase-transformed layer of material on the component surface, commonly referred to as 'white layer' [2,3] because of its white appearance under an optical microscope. The white layer is harder than the bulk material, and is often associated with tensile residual stresses. It is often assumed that a white layer is detrimental to fatigue life though its effect on service life is poorly understood.

Since hard turning is capable of producing particular surface integrity, it is important to define what surface integrity is considered to be. A clear understanding of the types of surface integrity attainable in hard turning will not only provide key insight to the machining process itself, but also provide a basis for determining the benefits to a turned component's life. This study will investigate surface topography, surface roughness, micro-hardness, subsurface microstructure, and residual stresses of the turned AISI 52100 components.

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doi:10.1016/j.msea.2004.12.012

The objectives of this study are to: (1) identify four types of distinct surface integrity that may significantly influence component life; (2) test the attainability of the types of surface integrity through hard turning tests with suitable process parameters; and (3) investigate the effects of the selected process parameters on surface integrity. This investigation will provide an insight to the ability of attaining desired surface integrity through the effects of established process parameters.

2. Literature review

Fatigue life is one of the main design criteria for hard-machined components [4], and surface integrity significantly influences fatigue life. One critical question faced in the hard turning industry concerns what surface integrity can be produced. Another one is whether surface integrity factors are controllable in hard turning. The true effects of residual stress and white layer on fatigue life are very controversial topics, but distinct surface integrity may have significant impact on fatigue life. Therefore the following four types of surface integrity encountered in hard machining were produced.

- Fresh surface FS-1 (defined in Table 1) free of white layer – residual stress pattern A (residual stress profile with a negative slope in the near-surface and deep maximum compressive residual stress in the subsurface).
- Fresh surface FS-2 (defined in Table 1) free of white layer – residual stress pattern B (more compressive residual stress in the near-surface but shallow maximum compressive residual stress in the subsurface compared with residual stress pattern FS-1).
- Thick white layer surface WL-1 (Table 1) with large tensile residual stress.
- Thin white layer surface WL-2 (Table 1) with large tensile residual stress.

While establishing process parameters for the four types of surface integrity might seem relatively easy, it should be noted that the combination of the ‘best’ parameters might have very complex and often undesired effects on surface integrity. For example, while increasing the cutting speed has been seen to increase machining efficiency, it may also increase temperatures and induce tensile residual stress and allow the risk of white layer formation.

2.1. Surface finish

Several studies [5–7] have shown that hard turning may produce equivalent, if not better, surface finish to grinding. Surface finish is nominally defined by feed and cutting edge geometry such as edge radius and nose radius. Theoretically, the increased tool nose radius can decrease surface roughness, or in other words increase the surface quality. However, the use of large nose radius to achieve better surface finish is often limited by cutting edge plowing. Since fatigue damage may initiate from the component surface, surface finish will have a great influence on the fatigue life [8]. Surface irregularities such as feed marks on the component surface pose a great threat to fatigue crack nucleation. Mirrored surfaces give improved fatigue life, while fatigue life of coarse or rough surfaces deteriorates. It is desirable in industry to obtain mirror surface finish of bearing assembly, shaft, axle, etc. without adding an additional finishing process. Therefore it is important to obtain the best surface finish possible from hard turning process. It is not known at present that what relation between surface finish and surface integrity such as white layer.

2.2. Residual stress

Residual stress pattern induced by hard turning is critical for component life and corrosion resistance. The residual stress profile is significantly influenced by feed, cutting speed, and cutting edge geometry. It was found that increasing the feed rate will cause larger compressive residual stresses or shift the maximum compressive residual stress deeper into the subsurface [6,9,10]. The increased radius of a cutting tool will also produce larger compressive residual stress [6,11]. The existence of a white layer is often associated with large magnitude of tensile residual stress in the near surface [12]. It is generally agreed that surface tensile residual stress reduces fatigue life [2,13–15] and compressive residual stress improves it [16,17]. A few studies [4,6,16] have shown that residual stress profile rather than surface residual stress has significant influence on rolling contact fatigue (RCF) and deep compressive residual stress seems to be more beneficial to RCF life than shallower compressive residual stress of greater magnitude. This suggests that residual stress profile has more influence on fatigue damage than surface residual stress alone. But, what residual stress profile pattern will improve RCF is still a mystery.

Table 1
Cutting conditions for distinct surface integrity

Cutting conditions	Fresh surface #1 (FS-1)	Fresh surface #2 (FS-2)	White layer #1 (WL-1)	White layer #2 (WL-2)
V (m/min)	106.8	106.8	169.2	169.2
f (mm/rev)	0.1016	0.0254	0.0254	0.0254
DoC (mm)	0.254	0.254	0.254	0.254
VB (mm)	0	0	0.7	0.4